Collaboration in Controller-Pilot Communication

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I. Overview

Like other forms of dialogue, ATC communication is an act of collaboration between two or more people. Collaboration progresses more or less smoothly depending on speaker and listener strategies. For example, we have found that the way controllers organize and deliver messages influences how easily pilots understand these messages, which in turn determines how much time and effort is needed to successfully complete the transaction. In this talk, I will introduce a collaborative framework for investigating controller-pilot communication and then describe a set of studies that investigate ATC communication from two complementary directions. First, we focused on the impact of ATC message factors (e.g., length, speech rate) on the cognitive processes involved in ATC communication. Second, we examined pilot factors that influence the amount of cognitive resources available for these communication processes.

These studies also illustrate how the collaborate framework can help analyze the impact of proposed visual data link systems on ATC communication. Examining the joint effects of communication medium, message factors, and pilot/controller factors on performance should help improve air safety and communication efficiency. Increased efficiency is important for meeting the growing demands on the National Air System.

II. Collaboration in ATC Communication

We analyzed ATC communication by adapting a general model of collaboration (Clark & Schaefer, 1989). Similar approaches have been used to analyze many kinds of dialogue, including human-computer interaction and automated voice systems (Karis & Dobroth, 1991). According to this view, transactions between speakers and listeners involve three collaborative phases, which participants accomplish by using several types of speech acts (Figure 1, see Morrow, Rodvold, & Lee, 1994, for more detail). These phases provide several points of comparison between voice and data link. These comparisons show how the same collaborative function can be accomplished in different ATC communication systems.

A. Collaborative phases

Initiate transaction. The speaker first attracts the listener's attention in order to initiate or open the transaction. Typically, air-ground ATC transactions begin with aircraft or facility call signs. Stress and intonation can also be critical for attracting attention in voice communication. In data link systems, message announcement chimes and visual alerts on the data link display may be used to start the transaction (ATA, 1992).

Present message. The speaker presents the message once the transaction is initiated. Commands, reports, or requests are presented by voice or computer. Understanding these messages requires cognitive processes such as word recognition, parsing, and updating a mental model of the current situation with the new information.

Accept message. Communication requires more than simply presenting and understanding messages-- The speaker and listener must collaborate in order to accept the message as mutually understood. This is particuarly important in ATC communication, which requires accurate understanding at a detailed, utterance by utterance level (Morrow et al., in press). In the current voice environment, acceptance rests upon pilot acknowledgments with readback and callsign. The controller in turn must "hear back", or monitor the acknowledgement to ensure that the message was understood. Several acceptance procedures have been proposed for data link systems, including a digital accept/reject response and an intracrew readback (ATA, 1992). In either voice or data link systems, the controller and pilot must agree before continuing that they understand the message and share a mental model of how the intended actions will change the flight situation. In ATC parlance, this phase is called "closing the communication loop".

B. Cognitive Resources and collaboration

The cognitive processes underlying collaboration depend on speaker and listener cognitive resources, which are limited in quantity. For example, noticing, understanding, and accepting messages require selective attention and working memory capacity. The constraints imposed by limited cognitive resources is often illustrated by a diagram of the flow of information

through a series of processing steps. However, this individual-centered approach must be expanded to include the shared cognitive resources required by collaborative effort-- the speaker and listener resources needed to achieve mutual understanding (Figure 2). For example, pilot responses such as partial acknowledgments can increase demands on controller working memory by forcing controllers to repeat the message and to continue monitoring the transaction. This increases the overall shared resources needed to close the transaction. The notion of collaborative effort has been useful for analyzing telephone dialogue (Clark & Schaefer, 1989) and crew coordination (Kanki, Lozito, & Foushee, 1989). Our studies have examined trade-offs of individual and collaborative effort in controller-pilot communication.

C. Factors influencing available cognitive resources

The success of communication depends on available individual and collaborative cognitive resources as well as the demands imposed on these resources by communication. The amount of resources available for communication depends on short term factors such as fatigue and distraction and longer term factors such as age and experience (Morrow & Rodvold, in press). The second set of studies that I'll describe examined the influence of pilot age on ATC communication.

D. Communication problems

Several types of problems tend to arise when available resources do not meet task demands during each collaborative phase.

Initiate transaction. Problems during initiation often relate to attention failures. For example, aircraft crew may not hear an ATC call because they talk over the message. They may also misunderstand the intended addressee, creating callsign confusions. Initiation problems have been an important impetus for discrete address data link systems (ATA, 1992).

Present message. A transaction may be successfully initiated, but message is misunderstood or misremembered because message presentation overloads working memory. The visual data link medium should reduce memory problems, although message complexity could amplify problems associated with poor data link menu or interface design.

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Accept message. Problems during the acceptance phase often relate to failure to follow acknowledgment procedures. For example, controllers and pilots may fail to explicitly close transactions because of missing acknowledgments (Morrow et al, 1994). There is also a concern that acknowlegment delays may disrupt data link transaction organization (ATA, 1992). The present studies focused on problems related to presenting and accepting messages.

III. Studies of ATC Communication

So far, I've sketched collaborative phases in ATC transactions, cognitive processes and resources involved in each phase, and possible communication problems. Our studies examined how pilot communication problems arise when complex ATC messages tax cognitive resources. We focused on message complexity because it is a concern in the National Air System (Billings & Cheany, 1981; Cardosi, 1993; Morrow, Lee, & Rodvold, 1993) and because manipulating complexity helps to map relations between demands imposed by message and medium factors, available cognitive resources, and communication problems. It also helps illustrate trade offs between individual and collaborative effort. For example, why do controllers produce complex messages, and what are the consequences of this strategy?

We started with a field study in order to generate hypotheses about problems related to message complexity. This was followed by laboratory studies that tested some of the hypotheses. These studies were conducted at NASA-Ames Research Center. A second set of laboratory studies (conducted at Stanford Medical Center) compared the performance of older and younger pilots on ATC communication tasks. According to cognitive aging theory (Salthouse, 1985), older pilots should have fewer cognitive resources than their younger counterparts. Therefore, we can indirectly examine the role of resources in ATC communication by means of this age comparison. These studies also relate back to the concept of collaborative effort-- pilots or controllers with fewer cognitive resources may be more likely to use strategies that minimize their effort at the expense of the other person.

A. Message complexity and ATC communication: Field study

Introduction. As a first step, Michelle Rodvold and I analyzed communication between controllers and pilots during daily operations in the terminal environment. Before this study, there was little information about routine ATC communication other than from incident/accident analyses. Therefore, we wanted to collect base rate information on the frequency of problems related to message complexity. The study would also provide a snapshot of collaborative processes in routine ATC communication.

Method. We collected 42 hours of taped communication (almost 8000 transactions) from four of the busiest TRACONs in the United States. Communication was transcribed and coded utterance by utterance for speech acts and topics (Figure 3; see Morrow, et al, 1993 for more detail). We also focused on nonroutine transactions, where the pilot or controller interrupts routine information transfer in order to clarify miscommunication, for more elaborate analysis of collaborative strategies (Morrow et al., 1994).

Results. First of all, longer messages (with 3 or more information units such as commands and reports) occurred in 5-20% of transactions, depending on the TRACON sample. More complex messages were associated with pilot comprehension and memory problems. For example, readback errors increased with message length (Figure 4). A similar pattern has been found for transactions in the enroute environment (Cardosi, 1993). Analysis of readback errors in our sample suggested that long messages taxed working memory. For example, incorrect digits in pilot readbacks often came from other numbers in the same message (intrusion errors), suggesting the error was due to interference.

Message complexity also disrupted the acceptance phase of transactions. Pilot acknowledgements were more streamlined after longer ATC messages, since the number of partial readbacks increased with message length. Thus, after delivering long messages, controllers are more likely to have to get back on the radio and request full acknowledgment.

Message length also influenced the way in which pilots read back the message (Figure 5). Pilots coped with longer messages by using strategies that minimized memory load (in

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addition to reading back less information). After shorter messages, they tended to say their call sign before the readback, as recommended by the Airmen's Information Manual. After longer messages, they tended to say the call sign after the readback. While this strategy may minimize memory load (repeat the new information first), it complicates the hearback because the controller has to wait until the end of the readback to make sure that the correct pilot responded.

Pilots also tended to repeat short messages verbatim, with commands in the same order as in the message. With longer messages, they tended to paraphrase and to repeat commands in a different order. These findings are not surprising in light of laboratory studies showing that verbatim memory tends to drop off after complex messages and/or long retention intervals (Anderson, 1980). But they also make an important point about collaboration in the ATC environment-- Readbacks after longer ATC messages tend to be less similar to the message in terms of terminology and information order, which may complicate the hearback part of the communication loop. Longer messages also tend to increase the number of communication problems, which lead to nonroutine transactions in which the communication is clarified (Cardosi, 1993). These transactions are longer than routine transactions and less efficient because the extra turns are devoted to clarifying old information rather than presenting new information. ATC language is also less standard and more complex in nonroutine transactions, which may lead to further confusion (Morrow et al., 1994).

In summary, our field analyses suggest a trade-off between individual and collaborative effort (Figure 6). Controllers sometimes deliver long, complex messages, perhaps to reduce turn-taking time and thus their own cognitive effort. These messages may overload pilots' cognitive resources so that the pilots misunderstand the message, request clarification, or adopt acknowledgement strategies that ease demands on memory. Any of these consequences can increase the difficulty of accepting the message and closing the transaction, resulting ultimately in greater collaborative effort.

B. Message complexity and ATC communication: Part-task simulation study

Introduction. We conducted a part-task simulation study to provide more conclusive evidence for the impact of message complexity on communication (see Morrow & Rodvold, 1993 for more detail). This study was conducted at NASA in collaboration with Michelle Rodvold, Sandy Lozito, Alison McGann, and Kevin Corker. With the help of several controllers and pilots, we created flight scenarios in which pilots were vectored by ATC in enroute and terminal environments. ATC messages were delivered in two ways: One long message with 4 commands (e.g., heading, altitude, speed, frequency) or a pair of short messages with 2 commands each. By delivering the same content in different ways, we could examine message length independent of content. Because controllers delivering two messages to the same aircraft would want to minimize communication time, we decided on a brief interval between delivering each message, roughly 10 sec.

Based on the earlier field results, we expected pilots to have more communication problems when confronted with the longer messages-- more requests for clarification and readback errors. However, short messages may also create problems. Because the second message of the sequence is delivered so quickly after the first, it may interfere with the pilot's response to the earlier message, resulting in delayed requests to clarify this message. The impact of these message factors on data link as well as voice communication was examined in a parallel study. Some data link findings will be mentioned at the end of the talk.

Method. The part-task laboratory consisted of (a) Workstation simulating an ATC radar station; (b) Workstation simulating a flight deck display; (c) Macintosh computer that presented the pre-recorded ATC messages. These computers were networked so that the controller could track the subject's aircraft on radar and control delivery of the messages to the flight deck display. The controller and pilot were also linked by a telephone-radio system. The flight scenarios imposed experimental control but also allowed for interactive communication. Scripted ATC messages were recorded, digitized, and sent by the controller to the pilot via

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computer. Pilots responded to these messages as they flew, and the controller was present in order to handle radio clarifications. Sixteen air carrier pilots participated in the study.

Results. Figure 7 shows that pilots were more likely to misunderstand the controller when too much information was presented in one message. They were more likely to ask for clarification after longer messages than after the two short messages combined. They also made more readback errors after longer messages (18% after long messages, 8% after short messages).

Problems associated with short messages differed from those after long messages (Figure 8). Pilots initially understood the first short message-- In most problems, they had first correctly read back the commands immediately after the first short message. However, they often forgot all or part of the first message by the time the second occurred-- Most of the delayed problems were requests for repeat or were incorrect requests for confirmation. These incorrect requests often contained intrusions, with one or more digits from the second message. Thus, pilots usually understood the first short message but then forgot part of it either because the second one created interference or delayed response to the first.

We recently conducted a second part-task study in order to systematically examine the impact of message interval on voice and data link communication (see Morrow, 1994 for more detail). While message interval was fixed in the first study, it was manipulated in this follow-up experiment. The second message was delivered either 5 sec or one min after the readback of the first message. In addition to voice and data link communication, we examined a mixed voice/data link environment where a voice ATC message was followed by a data link message, or viz versa. The mixed environment was examined because parts of the ATC system will likely resemble this hybrid when data link is introduced into the current environment (ATA, 1992).

Figure 9 shows that more voice communication problems (e.g., requests for repeat) occurred when voice messages were presented with short rather than long intervals (the difference between voice-only and mixed environments was not significant). Unlike the previous study, these problems usually related to the second rather than the first message of the

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sequence. Pilots delayed responding to the second message in order to complete their response to the first, and thus sometimes had to clarify the second message. Nonetheless, both part-task studies show that communication problems can arise from time pressure imposed by a rapid sequence of ATC messages.

The findings from these laboratory studies converge with the field results to show trade-offs between individual and collaborative effort in ATC communication-- Controllers may try to save time and effort by delivering too much information in one message or by delivering messages in quick succession. However, these strategies may increase collaborative effort and reduce communication efficiency by creating pilot comprehension or memory problems.

C. ATC Message factors and available cognitive resources: Age and practice

Introduction. So far we've examined comprehension and memory problems in ATC communication by investigating the influence of message delivery on ATC communication. The final studies examined how communication depends on the cognitive resources that pilots have available for meeting the demands imposed by communication. These studies were conducted at Stanford Medical Center in collaboration with Von Leirer, Jerry Yesavage, Joy Taylor, and Nancy Dolhert.

Because aging is often associated with a gradual decline in cognitive resources such as working memory capacity (Salthouse, 1985), comparing older and younger pilots provides a way to analyze the impact of cognitive resources on ATC communication. While older pilots may usually perform as well as younger pilots (e.g., because of selection effects, compensation of experience for age declines), age differences may arise for difficult ATC tasks. Therefore, we examined older and younger pilot performance on scenarios similar to our earlier studies (Morrow, Yesavage, Leirer, & Tinklenberg, 1993). The earlier studies suggest that long messages impose heavy demands on working memory. Such messages may particularly penalize older pilots if they have fewer cognitive resources to devote to communication, especially because they have to divide attention across other flying tasks while communicating. We also examined if practice on the communication tasks differentially improved older pilot

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performance. This might occur if older pilots were relatively unfamiliar with complex ATC communication tasks to begin with. In addition to providing a window on cognitive processes in ATC communication, findings about aging and pilot performance may have implications for the Age 60 retirement rule for Part 121 pilots in the United States.

Method. Fifteen older (Mean age= 38 years) and 16 younger (mean age=26) private license pilots flew a light single engine aircraft simulator with computer-generated out- the-window visuals. Older and younger pilots did not differ in terms of health, education, or flying experience. As in the part-task studies, ATC messages were pre-recorded and the scenarios involved vectoring in a terminal environment. Pilots flew 12 flights and performance was averaged across each set of 3 flights. Therefore, we examined ATC communication (readback and execution errors) and flying performance for older and younger pilots over the 4 flight sets.

Results. Figure 10 shows that older pilots made more readback and execution errors than younger pilots. Practice improved performance for both age groups but did not reduce age differences. Readback errors included intrusions from other parts of the message, providing further evidence that long messages can overload working memory. Finally, age differences were minimal for flying performance that did not depend on communication (e.g., deviation from center line on take off and landing). Thus, the older pilots generally flew as well as the younger pilots, but they had more difficulty with the heavy memory demands imposed by the communication task.

D. ATC Message factors and cognitive resources: Age, message length, and speech rate

Introduction. We also examined the joint effects of message complexity and pilot age on communication (Taylor et al, in press). Older and younger pilots in this study responded to messages varying in length and speech rate. "Speedfeed" is a frequent pilot complaint (Morrison & Wright, 1989), and laboratory studies show that recall declines as speech rate increases, particularly for older adults (Stine, Wingfield, & Poon, 1986). Therefore, faster as well as longer ATC messages should increase demands on cognitive resources and produce

communication problems. Older pilots may be particularly vulnerable to these messages because of age-related resource declines. On the other hand, speech rate effects are reduced for more meaningful or predictable texts (Stine, et al., 1986). Thus, older pilots may be able to compensate for reduced cognitive resources by relying on knowledge of ATC message structure.

To more directly test if the impact of message complexity on communication is mediated by working memory limits, individual differences in working memory capacity were measured by the WAIS-R digit span test. Correlations between span scores and communication errors would provide more direct evidence that the errors reflect working memory limits.

Method. Fifteen older (Mean age= 61) and 15 younger (mean age=28) pilots with instrument ratings flew in the same simulator as in the previous study. Half of the messages in each scenario contained 3 commands and half contained 4 commands. The messages were recorded by a controller at a typical speech rate (235 wpm). For both long and short messages, half were time-compressed (while minimizing pitch distortion) to produce a rate that was 50% faster than the normal version.

Results. Figure 11 shows that older pilots again made more message execution errors. In addition, longer messages (long=45%, short=23%) and messages presented at the faster rate (fast=37%, normal=31%) produced more errors. Age and message complexity had additive effects on communication. Thus, age differences were not magnified by difficult messages. Notably, pilots with higher span scores produced fewer errors (r=-.47), providing some evidence that message factors influenced performance through their effects on working memory.

Discussion. These studies show that aging can influence pilot performance of very demanding communication tasks. However, the studies involved noncommercial pilots. Using pilots with relatively low levels of experience may overestimate age effects in pilot performance. In fact, we have found some evidence that expertise reduces age differences in a laboratory readback task (Morrow, Leirer, Fitzsimmons, & Altieri, 1994). Nonetheless, the pilot age studies

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suggest that individual differences in performance may be useful for studying the role of cognitive resources in ATC communication.

E. ATC communication medium

I'll conclude by summarizing some data link findings from our part-task studies, which show how ATC message factors can interact with the communication medium to influence pilot-controller communication. The first part task study found that while message length had a large impact on voice communication, it had little effect on data link acknowledgement time or requests for clarification (McGann, Lozito, & Corker, submitted). Because of the relatively permanent visual medium, complex ATC messages appear to impose few demands on pilot working memory in data link systems. Of course, message complexity could become an issue if the menus and interface in data link systems impose demands on pilot working memory.

Data link communication was not immune to problems in our studies. For example, the short interval between messages slowed data link as well as voice communication in both part-task studies. The fact that the dynamics of message delivery can influence data link as well as voice communication reinforces concerns about introducing data link into busy terminal environments (ATA, 1992). These kinds of studies should help identify collaborative strategies for coping with dynamic communication in terminal environments, whether voice or data link is used.

IV. Conclusions

In summary, we have investigated how pilots and controllers collaborate to ensure mutual understanding in busy environments. We focused on readback/hearback procedures because they are essential to safe and efficient communication. The effectiveness of these procedures depends on the demands on pilot and controller cognitive resources imposed by ATC message and medium factors, as well as on available cognitive resources. For example, our field and laboratory studies show that problems arise in voice environments when pilot working memory is overloaded by long, fast messages, or by shorter messages presented in quick succession. Additional time and effort is then needed in order to clarify the problem and accept the message

as mutually understand, creating increased collaborative effort. Pilots can also increase controller workload by not following acknowledge procedures. For example, missing or partial acknowledgments may force the controller to repeat the message.

Our studies of pilot age and ATC communication suggest that complex or nonstandard communication may particularly tax older (or fatigued) pilots and controllers, who may have fewer resources to devote to the task. Therefore, they are more likely to use short cuts that reduce their own effort at the expense of collaborative effort. Some collaborative problems may be alleviated by a change in communication medium, while others remain. With visual data link, pilots may be able to easily handle long ATC messages but still have problems with a series of messages delivered in quick succession.

These findings suggest several recommendations for improving voice communication procedures, such as the optimal length and timing of ATC messages in the terminal environment. The collaborative framework also has training implications. Pilot and controller training should stress the importance of trade-offs between individual and collaborative effort-- When individuals reduce their own effort at the expense of other participants, everyone's workload tends to increase and accuracy and efficiency suffers. The concept of collaboration also has broader, more organizational implications. Pilots and controllers are more likely to collaborate during air-ground communication if they understand each other's responsibilities and constraints. Collaboration must be fostered rather than inhibited by organizational boundaries (SAE ARD #50045, in preparation).

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